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SEARCHING FOR INVISIBLE AND ALMOST INVISIBLE PARTICLES AT e^+e^- COLLIDERS

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Abstract

We explore the techniques, cross sections and expected signal significance for detecting invisible and almost invisible particles at LEP2 and the NLC by means of a hard photon tag. Examples from supersymmetry include the lightest chargino and second lightest neutralino when their masses are nearly the same as that of the lightest neutralino (the LSP), and invisibly decaying sneutrinos. The importance of particular features of the detectors is discussed, instrumentation for vetoing a fast e^+ or e^- in the beam hole being especially crucial.

1 Introduction

Models in which there are new particles that are either themselves invisible, or that decay to invisible or nearly invisible final states, abound in particle physics. For example, one of the most popular and attractive models for physics beyond the Standard Model (SM) is supersymmetry (SUSY). The lightest supersymmetric particle (LSP, normally the lightest neutralino, $\widetilde{\chi}_1^0$) of SUSY is invisible under the usual assumption of R-parity conservation. Other (heavier) supersymmetric partners of known particles (the sparticles) are usually easily detectable at LEP2 and the next linear e^+e^- collider (NLC) via events with energetic jets and/or leptons and missing energy, when the fraction of energy carried by the LSP and neutrinos in sparticle decays is not too large. This is the case for the most popular model scenarios. However, as outlined later, there exist SUSY models in which potentially visible jets/leptons from decays of many and perhaps all the lower-mass sparticles are either altogether absent or very to extremely soft. A heavy lepton doublet (L^-, L^0) where the L^0 is stable in the detector and $m_{L^-} - m_{L^0}$ is very small so that the ℓ^- from the $L^- \to \ell^- \overline{\nu} L^0$ decay is very soft provides another physics scenario which could be missed without employing a special approach [1]. Scenarios with extra scalar bosons have been proposed in which some are invisible because of degeneracy [2]. It is thus a matter of some urgency to explore techniques, and

to specify the required detector characteristics, that will maximize our ability to detect invisible or 'nearly invisible' particles (denoted by IP and NIP, respectively) *and to determine their mass.* If more than one IP and/or NIP is present, the techniques we discuss could allow for separation of the different signals and individual determination of masses, depending upon statistics.

Even if a NIP decays to visible, but soft, particles, triggering on inclusive NIP pair production is problematical. Typically, the mass difference between the NIP and its invisible decay products must be $\gtrsim 10\,\mathrm{GeV}$ [3] for inclusive pair production to be detectable in the presence of backgrounds. For very small mass differences, the NIP would develop a long enough lifetime that, if it is charged, a short track in the vertex detector might be visible; the problem would be to trigger on the event. Further, even if isolation of signal events at the inclusive level is possible, it could be very difficult to determine the mass of the particles being produced via the usual spectrum endpoint procedures. The possible solution to all these problems is to require that a tagged photon be produced in association with large missing energy from the pair of IP's or NIP's. This is an idea that originated for counting neutrinos [4], and has since been employed for a number of entirely invisible SUSY sparticles, see for example Refs. [5, 6]. In this paper we emphasize photon tagging in the NIP context.

We focus particularly on some previously unexplored scenarios in which the lightest chargino could be nearly invisible. A common assumption regarding supersymmetry breaking is that the gaugino masses are universal at the GUT scale, M_U. The renormalization group equations then imply that the gaugino masses at scales below a TeV are roughly related by $M_3 \sim 3 \times M_2$ and $M_2 \sim 2 \times M_1$, where M_3 is the gluino mass and M_2 and M_1 are the $SU(2)$ and $U(1)$ gaugino masses. Since the μ parameter that also enters the chargino and neutralino mass matrices is typically large, the above relations imply that the $\widetilde{\chi}^0_1$ LSP is mainly of the $U(1)$ bino variety with mass of order M_1 and the lightest chargino, $\widetilde{\chi}^+_1$, is primarily a wino with mass of order M_2. This implies significant mass splitting $\Delta m_{\tilde{\chi}_1} \equiv m_{\widetilde{\chi}^\pm_1} - m_{\widetilde{\chi}^0_1}$, so that observation of $\widetilde{\chi}^+_1\widetilde{\chi}^-_1$ production in e^+e^- collisions is straightforward [3]. However, it is not impossible that the M_U boundary conditions are quite different and that $\Delta m_{\tilde{\chi}_1}$ could be small, perhaps *very* small. A small mass difference arises, in particular, in two cases:

(i) High-μ scenario: [1] if M_2 is substantially smaller than M_1, and $\mu \gg M_{1,2}$ then the $\widetilde{\chi}^0_1$ and $\widetilde{\chi}^+_1$ are both wino-like and closely degenerate with $m_{\widetilde{\chi}^0_1} \sim m_{\widetilde{\chi}^\pm_1} \sim M_2$.

(ii) Low-μ, large-$M_{1,2}$ scenario: if $\mu \ll M_{1,2}$, then $\widetilde{\chi}^0_1$, $\widetilde{\chi}^0_2$ and $\widetilde{\chi}^+_1$ are all higgsino-like and nearly degenerate with masses $\sim \mu$.

[1] In a separate paper [7] we shall explore in greater depth a particular string model that leads to this scenario.

Values of $\Delta m_{\tilde{\chi}_1} \lesssim 10\,\mathrm{GeV}$ (*i.e.* in the problematical region for normal inclusive detection) are not at all improbable in either scenario, being almost automatic in scenario (i) and requiring only $M_{1,2} \gtrsim 500\,\mathrm{GeV}$ in scenario (ii) (*i.e.* well within the natural range for supersymmetry breaking).

The most challenging situation arises if $\Delta m_{\tilde{\chi}_1}$ lies below about a GeV, since then the visibility of the $\widetilde{\chi}_1^{\pm}$ comes into question. In case (ii), $\Delta m_{\tilde{\chi}_1} \lesssim 1\,\mathrm{GeV}$ implies that $m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^{\pm}}$ and $m_{\widetilde{\chi}_2^0} - m_{\widetilde{\chi}_1^0}$ will then more or less automatically also be of order a GeV or less; in contrast, in case (i) $m_{\widetilde{\chi}_2^0}$ is typically significantly larger than $m_{\widetilde{\chi}_1^0} \sim m_{\widetilde{\chi}_1^{\pm}}$. Extreme degeneracy ($\Delta m_{\tilde{\chi}_1} \lesssim 1\,\mathrm{GeV}$) between the lightest chargino and the LSP can be achieved in case (i) for $M_2 \gtrsim m_Z/2$ if $\mu \sim 1-2\,\mathrm{TeV}$, whereas in case (ii) $M_{1,2}$ must be $\gtrsim 5\,\mathrm{TeV}$ if $\mu \gtrsim m_Z/2$. (Values of $m_{\widetilde{\chi}_1^0}, m_{\widetilde{\chi}_1^+}$ below $m_Z/2$ are excluded by LEP1 limits on invisible/extra Z decays [7].) Thus, only scenario (i) can remain technically natural for $\Delta m_{\tilde{\chi}_1} \lesssim 1\,\mathrm{GeV}$, but from an experimental perspective scenario (ii) also deserves exploration in this limit.

In this paper, we show that $e^+e^- \to \gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ (and, in scenario (ii), $e^+e^- \to \gamma\widetilde{\chi}_1^0\widetilde{\chi}_2^0$) can yield a viable signal at LEP2 and the NLC for the mass-degenerate scenarios in question, depending upon the value of the common mass (denoted $m_{\tilde{\chi}}$). If the soft secondary tracks from $\widetilde{\chi}_1^{\pm}$ decay are visible (with substantial efficiency) then events containing a hard photon and the visible $\widetilde{\chi}_1^{\pm}$ remnants occur at a reasonable rate so long as $m_{\tilde{\chi}}$ is not too close to the threshold allowed by the required photon cut. If the $\widetilde{\chi}_1^{\pm}$ are effectively invisible, events of the type $e^+e^- \to \gamma + \not{E}_T$ will be adequately enhanced (for appropriate cuts) over Standard Model (SM) expectations as to provide the required signal for $m_{\tilde{\chi}}$ up to somewhat lower values. Whenever a signal is visible, at least an approximate determination of $m_{\tilde{\chi}}$ will be possible.

2 The Hard Photon Signals

We will begin by focusing on the case in which the light inos are effectively invisible so that the final state is $\gamma + \not{E}_T$. In practice, the only important signal processes are

1. $e^+e^- \to \gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-$; and, in scenario (ii),

2. $e^+e^- \to \gamma\widetilde{\chi}_1^0\widetilde{\chi}_2^0$.

   The only irreducible background is

3. $e^+e^- \to \gamma\nu\overline{\nu}$.

In both scenarios (i) and (ii) the $Z\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ and $Z\widetilde{\chi}_2^0\widetilde{\chi}_2^0$ couplings are small, implying that $\gamma\widetilde{\chi}_1^0\widetilde{\chi}_1^0$ and $\gamma\widetilde{\chi}_2^0\widetilde{\chi}_2^0$ final states have negligible rate. However, in scenario (ii) the $Z\widetilde{\chi}_1^0\widetilde{\chi}_2^0$ coupling is maximal and reaction (2) is important. The background from $e^+e^- \to \gamma\tau^+\tau^-$ in which *both* τ's decay to leptons or hadrons with small energy

(say below a few GeV or so), or disappear down the beam pipe, is negligible by comparison to reaction (3). A second, potentially very large, background is that from $e^+e^- \to e^+e^-\gamma$ events where neither the final e^+ nor e^- is detected. The techniques and experimental requirements for eliminating this background are discussed below. In our computations of the signal cross sections, we assume that slepton and sneutrino exchange diagrams can be neglected. In scenario (ii), this is automatically the case because the higgsino-like $\widetilde{\chi}^0_1, \widetilde{\chi}^+_1, \widetilde{\chi}^0_2$ have negligible coupling to $e\widetilde{e}, e\widetilde{\nu}$. As described in Ref. [7], the specific string model approach that leads to scenario (i) requires a large M_U-scale value of the soft supersymmetry breaking scalar mass parameter m_0, implying that most sfermions (except possibly the lightest stop) have masses $\gtrsim 1\,\mathrm{TeV}$, so that slepton and sneutrino exchanges can again be neglected. Note that squarks, sleptons and sneutrinos would then all be too heavy to be directly produced at the NLC, let alone LEP2. The only observable signals for SUSY at e^+e^- colliders would be those we now discuss.

We envision tagging the events using a photon that has substantial transverse momentum. For the study presented here, we require $p_T^\gamma \geq p_T^{\gamma\,\min}$, with $p_T^{\gamma\,\min} = 10\,\mathrm{GeV}$, and $10^\circ \leq \theta_\gamma \leq 170^\circ$, where θ_γ is the angle of the photon with respect to the beam axis, so as to guarantee that the photon enters a typical detector and will have an accurately measured momentum. We define $\gamma + \not{E}_T$ events by requiring that any other particle appearing in the 10° to 170° angular range must have energy less than $E^{\max}$, where $E^{\max}$ is detector-dependent, but presumably no larger than a few GeV. Kinematics can be used to show that we can eliminate the $e^+e^- \to e^+e^-\gamma$ background by vetoing events containing an e^+ or e^- with $E > 50\,\mathrm{GeV}$ with angle $\theta_{\min} \leq \theta_e \leq 10^\circ$ with respect to either beam axis, or with $E > E^{\max}$ and $10^\circ \leq \theta_e \leq 170^\circ$, *provided* $p_T^{\gamma\,\min} \gtrsim \sqrt{s}\sin\theta_{\min}(1+\sin\theta_{\min})^{-1}$ (assuming $E^{\max}$ is not larger than a few GeV). For $p_T^{\gamma\,\min} = 10\,\mathrm{GeV}$, this means that we must instrument the beam hole down to $\theta_{\min} = 1.17^\circ$. In fact, instrumentation and vetoing will be possible down to $\theta_{\min} = 0.72^\circ$ [8], implying that $p_T^{\gamma\,\min}$ could be lowered to $\sim 6.2\,\mathrm{GeV}$ without contamination from the $e^+e^- \to e^+e^-\gamma$ background. At LEP-192, beam hole coverage down to about 3.1° is needed when using a $p_T^{\gamma\,\min} = 10\,\mathrm{GeV}$ cut.

For ino masses above $m_Z/2$, the key observation for reducing the background reaction (3) and determining the ino mass is to note that the missing mass $m_{Z^\star} \equiv [(p^{e^+} + p^{e^-} - p^\gamma)^2]^{1/2}$ can be very accurately reconstructed. For signals with good overall statistical significance (in most cases N_{SD}, defined below, $\gtrsim 5$ is adequate) one can plot events as a function of $m_{Z^\star}$ and look for the threshold at $2m_{\tilde{\chi}}$ at which the spectrum starts to exceed the expectations from $\gamma\nu\overline{\nu}$. We define an overall statistical significance $N_{SD} = S/\sqrt{B}$ for the signal by summing over all events with $m_{Z^\star} > 2m_{\tilde{\chi}}$. Note, in particular, that this cut eliminates the Z-pole contribution to the $\gamma\nu\overline{\nu}$ background for $m_{\tilde{\chi}} > m_Z/2$. In practice, one can often do better (perhaps by 1σ) than this nominal N_{SD} value by zeroing in on those $m_{Z^\star}$ bins with the largest deviations from $\gamma\nu\overline{\nu}$ expectations.

In Fig. 1 we display our results. For scenario (i), the $e^+e^- \to \gamma\widetilde\chi_1^+\widetilde\chi_1^-$ signal and $e^+e^- \to \gamma\nu\overline{\nu}$ background cross sections are such as to yield (solid curves) $N_{SD} = S/\sqrt{B} \geq 5$ for $m_{\widetilde\chi} \lesssim 65\,\mathrm{GeV}$ ($\lesssim 200\,\mathrm{GeV}$) at LEP-192 (NLC-500) for total luminosities of $L = 500$ pb^{-1} (50 fb^{-1}), respectively. In contrast, for universal gaugino masses at M_U it is generally expected that chargino pair production can be observed up to very nearly $\sqrt{s}/2$. We note that the nominal 5σ signal observation requires a small systematic uncertainty in our knowledge of the background, given that $S/B \lesssim 0.2$ ($\lesssim 0.05$) at the $m_{\widetilde\chi}$ value at LEP-192 (NLC-500) where N_{SD} falls below 5. Thus, it could be that the $\gamma + \not\!\!E_T$ signal might not be viable all the way out to the nominal 5σ mass value.

In scenario (ii), the $\widetilde\chi_1^0$, $\widetilde\chi_1^\pm$ *and* $\widetilde\chi_2^0$ are all closely degenerate. In this case, the magnitude of the $\gamma + \not\!\!E_T$ signal depends upon whether or not we include $e^+e^- \to \gamma\widetilde\chi_1^0\widetilde\chi_2^0$ as a contribution. We will present N_{SD} values obtained for the $\gamma\widetilde\chi_1^+\widetilde\chi_1^-$ and $\gamma\widetilde\chi_1^0\widetilde\chi_2^0$ channels separately, keeping in mind that the mass degeneracy means that in the $\gamma + \not\!\!E_T$ channel they can be added together. From the results presented in Fig. 1 we see that the $\gamma + \not\!\!E_T$ signal from the $\gamma\widetilde\chi_1^+\widetilde\chi_1^-$ channel alone is much weaker in this scenario where the $\widetilde\chi_1^\pm$ are higgsino-like as compared to the previous scenario where they are $SU(2)$-gaugino-like. This is simply because the virtual Z-exchange contribution is suppressed when the $\widetilde\chi_1^\pm$ are higgsino-like (and thus belong to a doublet vs. triplet SU(2) representation). Without including the $\gamma\widetilde\chi_1^0\widetilde\chi_2^0$ channel LEP-192 (NLC-500) can only achieve $N_{SD} \geq 5$ for $m_{\widetilde\chi} \lesssim 45\,\mathrm{GeV}$ ($\lesssim 140\,\mathrm{GeV}$). For the combined $\gamma\widetilde\chi_1^+\widetilde\chi_1^- + \gamma\widetilde\chi_1^0\widetilde\chi_2^0$ channels LEP-192 (NLC-500) can achieve $N_{SD} \geq 5$ for $m_{\widetilde\chi} \lesssim 55\,\mathrm{GeV}$ ($\lesssim 170\,\mathrm{GeV}$), better, but still not as large a reach as for scenario (i).

By way of comparison, we also give results (dot-dashed curves) for the $\gamma + \not\!\!E_T$ signal deriving from $e^+e^- \to \gamma\widetilde\nu\overline{\widetilde\nu}$ when the $\widetilde\nu$ decays invisibly to $\nu\widetilde\chi_1^0$ with 100% branching ratio. $BR(\widetilde\nu \to \nu\widetilde\chi_1^0) \sim 1$ is typical of soft-SUSY-breaking models having $m_{1/2}$ (the common gaugino mass) substantially larger than m_0 (the common scalar mass) at M_U; an example is the very attractive Dilaton model with $m_0 = m_{1/2}/\sqrt{3}$ [9]. Detection of invisible sneutrinos in association with a photon tag was also considered in Ref. [6]; there, several other model contexts in which $BR(\widetilde\nu \to \nu\widetilde\chi_1^0) = 1$ or is large are reviewed. Our procedures differ from those of Ref. [6] in that we employ the $m_{Z^\star} \geq 2m_{\widetilde\nu}$ cut to maximize the signal significance. We conservatively compute the signal in the approximation that charginos are heavy. We see from Fig. 1 that a statistically significant signal ($N_{SD} = 5$) is not possible at LEP-192 for integrated luminosity of $L = 500$ pb^{-1}, whereas $m_{\widetilde\nu} \lesssim 100\,\mathrm{GeV}$ could be probed at the NLC with $L = 50$ fb^{-1}. (The signals found in Ref. [6] at LEP-192 are also well below the $N_{SD} = 5$ level.) Finally, we note that in these models the lighter $\widetilde\tau$ eigenstate, $\widetilde\tau_1$, can be nearly degenerate with the $\widetilde\chi_1^0$ (the crossover at $m_{\widetilde\chi_1^0} = m_{\widetilde\tau_1}$ often defines the upper limit on $\tan\beta$) in which case $\gamma\widetilde\tau_1\widetilde\tau_1$ production would provide the only viable signature for the $\widetilde\tau_1$.

For all the cases discussed above, we have explored whether increasing the minimum p_T^γ required at a given $m_{\widetilde{\chi}}$ or $m_{\widetilde{\nu}}$ would improve N_{SD}. Even though S/B can be improved at lower masses, the nominal N_{SD} worsens in all the cases examined. We also find that the distributions of signal and background in θ_γ are very similar (even in the $\gamma\widetilde{\nu}\overline{\widetilde{\nu}}$ case) so that additional θ_γ cuts do not help.

The more limited range of viability for the $\gamma + \not\!\!E_T$ signals in scenario (ii) is a concern. However, for $M_{1,2}$ values below a TeV (but μ still much smaller), the degeneracy among the $\widetilde{\chi}_1^0, \widetilde{\chi}_1^\pm, \widetilde{\chi}_2^0$ will be only approximate and the leptons from $\widetilde{\chi}_1^\pm \to \ell^\pm \nu \widetilde{\chi}_1^0$ or the photon from the one-loop decay $\widetilde{\chi}_2^0 \to \gamma\widetilde{\chi}_1^0$ (the decays $\widetilde{\chi}_2^0 \to \ell^+\ell^-\widetilde{\chi}_1^0, q\overline{q}\widetilde{\chi}_1^0$ and $\widetilde{\chi}_2^0 \to \ell^\mp\nu\widetilde{\chi}_1^\pm$ usually having much smaller branching ratio) would generally be visible.

This leads us to consider the case in which the $\widetilde{\chi}_1^\pm$ and $\widetilde{\chi}_2^0$ decay visibly, but the mass degeneracy is such that the visible decay products are quite soft. Once again, the hard photon trigger will be crucial. We have been unable to envision significant backgrounds to the types of events in question (assuming the $e^+e^- \to e^+e^-\gamma$ events are vetoed, as described earlier). In scenario (i) the signal events would contain a hard photon, large missing energy, and either two widely separated quasi-stable particle tracks, if the $\widetilde{\chi}_1^+$ has a long lifetime, or separated soft leptons, pions and/or jets. In scenario (ii), the $\gamma\widetilde{\chi}_1^0\widetilde{\chi}_2^0$ events would have a single extra soft isolated photon from the dominant $\widetilde{\chi}_2^0 \to \gamma\widetilde{\chi}_1^0$ decay. (Note that it would be possible to separate $\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ from $\widetilde{\chi}_1^0\widetilde{\chi}_2^0$ events.) If the backgrounds to these two types of $\gamma + \not\!\!E_T + soft/visible$ are truly negligible, then it is the absolute rate obtained by combining all such events that determines whether or not the events provide a viable signal.

Let us first focus on the $\gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ final state in scenario (i). The cross sections of Fig. 1 give event rates that are sizeable for chargino masses substantially above the values that can be probed by the $\gamma + \not\!\!E_T$ signal. For our cuts, we find about 25 (50) events at $m_{\widetilde{\chi}} = 80\,\mathrm{GeV}$ ($240\,\mathrm{GeV}$) at LEP-192 with $L = 500\ \mathrm{pb}^{-1}$ (NLC-500 with $L = 50\ \mathrm{fb}^{-1}$). With good efficiency either for detecting the $\widetilde{\chi}_1^\pm$ as quasi-stable particle tracks in the vertex detector or for detecting the $\widetilde{\chi}_1^\pm$ decay products (*i.e.* the soft pions, leptons or jets), these event numbers may be adequate. In scenario (ii), we find from Fig. 1 [10,7] ([25,11]) events at $m_{\widetilde{\chi}} = 80\,\mathrm{GeV}$ ($240\,\mathrm{GeV}$) for the $[\gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-, \gamma\widetilde{\chi}_1^0\widetilde{\chi}_2^0]$ final states at LEP-192 (NLC-500). These small numbers would appear to be quite marginal; probably one would be able to extract the signal obtained by combining the $\gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ and $\gamma\widetilde{\chi}_1^0\widetilde{\chi}_2^0$ events only for masses $\lesssim 75\,\mathrm{GeV}$ ($\lesssim 235\,\mathrm{GeV}$) at LEP-192 (NLC-500). A 5σ determination of the two signal levels separately would be possible only for a still more limited mass range.

3 Lifetime and Branching Ratios for the $\widetilde{\chi}_1^-$

In this section, we quantify the extent to which the lightest chargino might or might not be visible. We have computed the branching ratios and lifetimes for the

$\widetilde{\chi}_1^-$. In Fig. 2, we give explicit results for the (more natural) large-μ scenario (i). For very small $\Delta m_{\tilde{\chi}_1}$, $\widetilde{\chi}_1^- \to \ell^- \nu_\ell \widetilde{\chi}_1^0$ ($\ell = e, \mu$) is the only kinematically allowed decay mode. As the mass difference increases, $\widetilde{\chi}_1^- \to \pi^- \widetilde{\chi}_1^0$ opens up and remains dominant for $m_\pi < \Delta m_{\tilde{\chi}_1} \lesssim 1\,\mathrm{GeV}$. Above that, the $\widetilde{\chi}_1^0 \pi^- \pi^0$ and three-pion channels become important. The sum of the one-, two- and three-pion channels merges into $\widetilde{\chi}_1^- \to q' \overline{q} \widetilde{\chi}_1^0$ at $\Delta m_{\tilde{\chi}_1} \sim 1.5\,\mathrm{GeV}$. For still larger mass difference, $\widetilde{\chi}_1^- \to \tau^- \nu_\tau \widetilde{\chi}_1^0$ becomes kinematically allowed. Details of the calculations will appear in Ref. [7]. Here we simply note that the lifetime and branching ratios are essentially independent of $\tan\beta$ and the sign of the μ parameter. Finally, we note that scenario (ii) leads to very similar $\widetilde{\chi}_1^-$ branching ratios, but, for a given $\Delta m_{\tilde{\chi}_1}$, about a 40% longer lifetime. And, we have already noted that in scenario (ii) the dominant $\widetilde{\chi}_2^0$ decay is via one-loop graphs to $\gamma \widetilde{\chi}_1^0$ for small mass differences.

Let us now consider implications for $\gamma \widetilde{\chi}_1^+ \widetilde{\chi}_1^-$ production. Fig. 2(a) shows that the produced $\widetilde{\chi}_1^-$ and $\widetilde{\chi}_1^+$ will travel distances of order a meter or more (and thus appear as heavily-ionizing tracks in the vertex detector and the main detector) if $\Delta m_{\tilde{\chi}_1} < m_\pi$. For $m_\pi < \Delta m_{\tilde{\chi}_1} < 1\,\mathrm{GeV}$, 10 cm $> c\tau >$ 100 μm. For $c\tau$ near 10 cm, the $\widetilde{\chi}_1^\pm$ would pass through enough layers of a typical vertex detector that its heavily ionizing nature would be apparent. For $c\tau$ in the smaller end of the above range, one would have to look for the single charged pion from the dominant $\widetilde{\chi}_1^\pm \to \pi^\pm \widetilde{\chi}_1^0$ mode. It emerges at a finite distance of order $c\tau$ from the vertex and would have momentum $p_\pi \sim \sqrt{\Delta m_{\tilde{\chi}_1}^2 - m_\pi^2}$ in the $\widetilde{\chi}_1^\pm$ rest frame. The expected impact parameter resolution, $b_{\rm res}$, of a typical vertex detector (we looked at the CDF Run II vertex detector with the inner L00 layer in detail [2]) as a function of momentum is such that $c\tau / b_{\rm res} > 3$ for $\Delta m_{\tilde{\chi}_1} < 1\,\mathrm{GeV}$, with quite large values typical for $\Delta m_{\tilde{\chi}_1} < 0.5\,\mathrm{GeV}$. Such a high-$b$ pion in association with the γ trigger would constitute a fairly distinctive signal. As discussed in the previous section, detection of any heavily-ionizing track and/or *any* $\widetilde{\chi}_1^\pm$ decay product would greatly enhance the significance of the signal by removing the $\gamma \nu \overline{\nu}$ background. For $\Delta m_{\tilde{\chi}_1} > 1\,\mathrm{GeV}$, the $\widetilde{\chi}_1^\pm$ decay is prompt and one must look for the soft leptons or hadrons emerging from the decay. These might be difficult to detect if $\Delta m_{\tilde{\chi}_1}$ is not somewhat larger. For instance, for $1 < \Delta m_{\tilde{\chi}_1} < 2\,\mathrm{GeV}$, $\widetilde{\chi}_1^\pm$ decays lead to final states that are similar to those appearing in $\tau^\pm$ decays. Without the hard photon plus $\not{E}_T$ tag, backgrounds to inclusive $e^+e^- \to \widetilde{\chi}_1^+ \widetilde{\chi}_1^-$ from $\gamma\gamma \to \tau^+\tau^-$ might be difficult to overcome, even if the chargino pair events can be triggered on.

4 Final Remarks and Conclusions

We have considered techniques for detecting particles that decay invisibly or nearly invisibly at e^+e^- colliders, focusing on the implications for chargino detec-

[2]We thank H. Frisch for providing details. The NLC vertex detector can be built with similar characteristics (R. Van Kooten, private communication). The innermost vertex detector at LEP is at $r = 6.3$ cm, implying less sensitivity there.

tion of scenarios in which $\Delta m_{\tilde{\chi}_1} \equiv m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0}$ is small, including cases in which $\Delta m_{\tilde{\chi}_1}$ is neither small enough for the $\widetilde{\chi}_1^\pm$ to produce a visible track in the detector nor large enough for the leptons from $\widetilde{\chi}_1^\pm \to \ell\nu\widetilde{\chi}_1^0$ to have adequate momentum to be visible. We have demonstrated that if the $\widetilde{\chi}_1^\pm$ are effectively invisible, then $e^+e^- \to \gamma + \not{E}_T$ events with $p_T^\gamma \geq p_T^{\gamma\,\min} = 10\,\mathrm{GeV}$ will be detectable above the $e^+e^- \to \nu\overline{\nu}\gamma$ background for a substantial (but model-dependent) range of $m_{\widetilde{\chi}_1^\pm}$.

In order that $e^+e^- \to \nu\overline{\nu}\gamma$ be the primary background in the $\gamma + \not{E}_T$ channel, $e^+e^- \to e^+e^-\gamma$ events for which a fast final e^+ and e^- are not seen must be vetoed. At the NLC, for example, this implies that it is absolutely mandatory (and, apparently, straightforward) for the detectors to have instrumentation in the $\theta_{\min}$ to 10° portion of the beam hole, where $\theta_{\min} \sim 1.17^\circ$ for $p_T^{\gamma\,\min} = 10\,\mathrm{GeV}$.

We have delineated the lifetime and branching ratios of the $\widetilde{\chi}_1^\pm$. These can be used to determine the detector requirements and machine environment that would alleviate the necessity for employing the rather indirect $\gamma + \not{E}_T$ signal for supersymmetry. The hope is that one could observe the $\gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ events by tagging the photon, requiring large $\not{E}_T$ and looking, in addition, for the 'quasi-stable' particle tracks and/or the soft leptons or charged pions from the $\widetilde{\chi}_1^\pm$ decays. We urge the detector groups at LEP and planning groups for the NLC to examine carefully the question of whether or not there is a band in $\Delta m_{\tilde{\chi}_1}$ for which only the $\gamma + \not{E}_T$ signature (with the large $\gamma\nu\overline{\nu}$ background) can be employed. If tracks or remnants from the $\widetilde{\chi}_1^\pm$ are visible with good efficiency, we find that the predicted rates for $\gamma + \not{E}_T + soft/visible$ events are such as to yield a viable $\gamma\widetilde{\chi}_1^+\widetilde{\chi}_1^-$ signal for $m_{\widetilde{\chi}_1^\pm}$ substantially nearer to the kinematic limit implied by the photon trigger requirement than if only the $\gamma + \not{E}_T$ signature can be employed. In scenario (ii), similar statements apply to $e^+e^- \to \gamma\widetilde{\chi}_1^0\widetilde{\chi}_2^0$ events, where the soft leptons/pions are replaced by a single soft photon.

We stress that the $\gamma + \not{E}_T$ and $\gamma + \not{E}_T + soft/visible$ procedures are broadly applicable to isolating a signal for invisible and nearly invisible particles. The photon trigger also provides a general, and, quite possibly, the only, means for determining the mass of any such particle. Mass determination is accomplished by employing $m_{Z^\star} \equiv [(p^{e^+} + p^{e^-} - p^\gamma)^2]^{1/2}$ to look for the onset of signal events at $m_{Z^\star}$ equal to twice the mass of the particle in question. With good statistics, detection of several distinct $m_{Z^\star}$ thresholds can potentially be used to separate signals appearing at different mass scales due to different particles even when the associated events are indistinguishable on the basis of event characteristics.

In Ref. [7], we explore Tevatron and LHC detection of gluinos when $m_{\widetilde{g}}$ is near $m_{\widetilde{\chi}_1^\pm} \sim m_{\widetilde{\chi}_1^0}$. Despite the softness of the jets in $\widetilde{g} \to q'\overline{q}\widetilde{\chi}_1^\pm, q\overline{q}\widetilde{\chi}_1^0$ decays and the invisibility of the $\widetilde{\chi}_1^\pm$ decay products, we find that detection of gluino pair events in $jets + \not{E}_T$ final states will still be possible for much the same mass ranges as before. This is because gluino pairs have a high probability of being made in association with one or more energetic jets. Thus, both lepton and hadron machine data will allow us to probe supersymmetry even when mass splittings among the

light supersymmetric particles are small.

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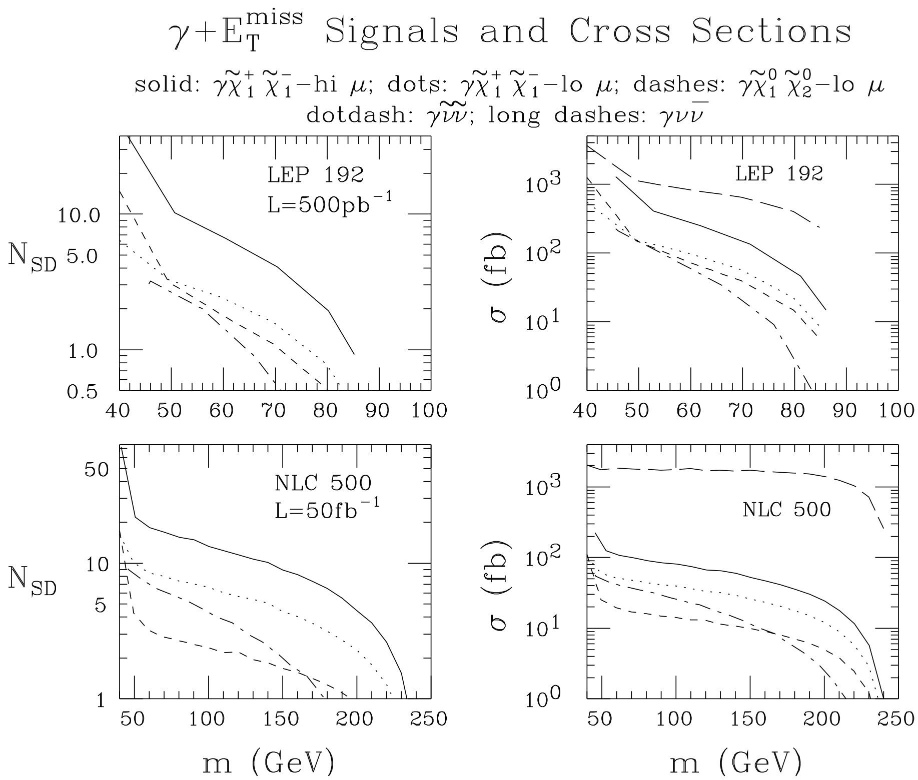

Figure 1: We plot the statistical significance $N_{SD} = S/\sqrt{B}$ in the $\gamma + \not{E}_T$ channel as a function of NIP mass m ($= m_{\tilde{\chi}}$ or $m_{\tilde{\nu}}$). In all cases B is computed from $e^+e^- \rightarrow \gamma\nu\overline{\nu}$ by integrating over $m_{Z^\star} \geq 2m$. Results for LEP-192 (with $L = 0.5$ fb^{-1}) and NLC-500 (with $L = 50$ fb^{-1}) are displayed. Also shown (right-hand panels) are the individual cross sections for signals and background (long dashes). We employ the cuts: $p_T^\gamma \geq 10\,\mathrm{GeV}$; $10^\circ \leq \theta_\gamma \leq 170^\circ$.

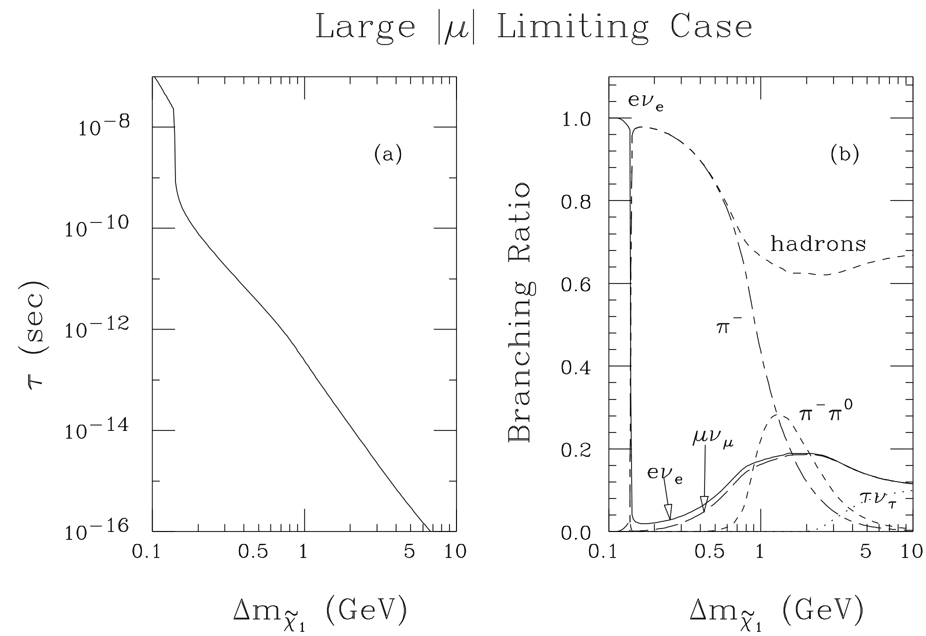

Figure 2: We plot for scenario (i) the lifetime (a) and branching ratios (b) for the $\widetilde{\chi}_1^-$ as a function of $\Delta m_{\tilde{\chi}_1} \equiv m_{\widetilde{\chi}_1^\pm} - m_{\widetilde{\chi}_1^0}$. For $\Delta m_{\tilde{\chi}_1} < 1.5\,\mathrm{GeV}$, we explicitly compute and sum the $\pi^-\widetilde{\chi}_1^0$, $\pi^-\pi^0\widetilde{\chi}_1^0$, $\pi^-\pi^0\pi^0\widetilde{\chi}_1^0$ and $\pi^-\pi^+\pi^-\widetilde{\chi}_1^0$ modes. These merge into and are replaced by a computation of the $q'\overline{q}\widetilde{\chi}_1^0$ width for $\Delta m_{\tilde{\chi}_1} > 1.5\,\mathrm{GeV}$.